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Aboveground biomass and nutrient allocation in an age-sequence of *Larix olgensis* plantations

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Abstract: Biomass and nutrient (N, P, K, Ca, Mg) stock in various aboveground tree components (stemwood, stembark, branches and leaves) were quantified in an age sequence of pure *Larix olgensis* plantations (20, 35, 53 and 69 years old) in Northeast China. The results show that the aboveground biomass allocation in various tree components was in the order of stemwood (62%–83%), branches (9%–21%), stembark (7%–11%) and leaves (1%–6%) for all stands. The proportion of stemwood biomass to total aboveground biomass increased whereas that of other tree components decreased consistently with stand age from 20 to 53 years old, but kept relatively constant with stand age from 53 and 69 years old. The nutrient allocation in various tree components generally followed the same pattern as the biomass allocation (i.e. stemwood > branches > stembark > leaves). The proportion of nutrient stock in leaves to total aboveground nutrient stock decreased consistently with increasing stand age, while that in stemwood increased with stand age from 20 to 53 years old but then decreased from 53 to 69 years old. The rate of nutrient removal for stands was estimated at different stand ages under different logging schemes, showing that the rate of nutrient removal would be unchanged when the rotation length was shortened to 20 years by the harvest of stem only, but greatly increased by the harvest of total aboveground biomass. The rate of nutrient removal would be a considerable reduction for all elements by debarking, especially for Ca.

Keywords: *Larix olgensis*; nutrient allocation; stand development; nutrient removal

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Introduction

In recent decades, one of the major issues of sustainable management of timber plantations is to solve the contradiction between the increased demand for timber production and the maintenance of environmental sustainability, i.e. soil fertility, water regime (Nambiar 1996; Laclau et al. 2003). Soil nutrient depletion in short and medium rotation plantations (i.e. Chinese fir, eucalyptus, Douglas-fir) has been observed worldwide as substantial amounts of nutrients are directly removed by harvesting timber and indirectly lost by soil erosion and leaching after harvest (Reynolds & Stevens 1998; Ranger et al. 2002; Ma et al. 2007; Turner & Lambert 2008). For this reason, increasing interests are shown in assessing nutrient removal by harvesting forest (Laclau et al. 2000; Adegbidi et al. 2001; Ponette et al. 2001). Understanding of nutrient accumulation and allocation patterns in tree biomass at different stages of stand development is essential to evolve suitable strategies of nutrient management, as well as to optimize harvest scheme.

Larches (*Larix*) are important timber species in Northeast China, with the largest planting area and timber production. The statistics from the sixth National Forest Resources Inventory (1999–2003) showed that the total area of larch plantations in China reached 6.4×10^6 ha, of which 73% was distributed in the three provinces (Heilongjiang, Jilin, and Liaoning) of Northeast China (http://www.cfsdc.org/). In past decades, although soil fertility degradation has been extensively observed in this plantation (Liu et al. 1998; Sun 2005), little attention has been paid to ecosystem nutrient cycling. The maintenance of soil environment has been seldom considered in forest management (Liu 1995; Liu et al. 1995). To our knowledge, nutrient accumulation and allocation patterns in larch plantations during stand development have never been documented. In addition, the rotation length of larch plantation has been an important issue. The clear-cutting for stands in Northeast China is officially prescribed at more than 40 years old of larch plantations. However, some researchers suggested that the rotation length might be shortened to 20–35 years old to meet the increasing demand for small and medium

diameter log and to maximize economic benefit (Liu & Yu 1990; Zhao & Jiang 1995).

The present study examined the biomass and nutrient content in aboveground tree components of *Larix olgensis* plantations of four ages in northeast China. The objectives were to understand the biomass and nutrient allocation patterns during stand development, and to assess nutrient removal by different logging schemes (all aboveground biomass, stemwood, and stem with bark) at different ages.

Materials and methods

Site description and sampling

This study was conducted at the Wendao Forest Farm in Fushun County, Liaoning Province, China (N 41°45′–41°53′, E 124°1′–124°8′, 200–300 m, a.s.l.). This is a low hilly area, with the slope usually ranging between 10° and 25°. The climate is temperate continental monsoon, with four distinct seasons. The mean annual precipitation is approximately 800 mm, of which more than 70% falls during June to August. The annual mean temperature is about 7.8°C. The frost-free period lasts 150 days. The soil is a typical dark brown forest soil in Chinese Soil Taxonomy, with a thickness of 30–55 cm.

In August 2007, even-aged pure plantations of *L. olgensis* of four ages (20, 35, 53, and 69 years old) were selected for this study. The area of plantations for each age ranged from 4.4 to 22 ha, and all the stands were adjacent. The planting spacing was 2 m × 2 m for all stands, and no fertilization and no pruning were applied. The 40% and 50% thinning intensities (on the basis of remaining individuals) were applied at the ages of 18 and 25 respectively for the 35, 53, and 69 years old stands. Three plots (20 m×20 m) were randomly established for plantations at each age. Tree height and diameter at breast height (DBH) were measured for all trees within these plots. Five average trees in each plot were sampled for four different aboveground tree components (leaves, branches, stembark, stemwood). Leaves and branches (wood + bark) were collected from four directions of the middle crown. Stemwood and stembark were collected with an increment borer. Samples of the respective tree component from each plot were composited into one sample. Basic stand and soil characteristics are shown in Table 1.

Table 1. Characteristics of the experimental stands and soils (at depth of 0–20 cm)

Age (years)	Density ($tree \cdot ha^{-1}$)	Crown density	Basal area ($m^2 \cdot ha^{-1}$)	Mean DBH (cm)	Mean height (m)	Stem volume ($m^3 \cdot tree^{-1}$)	Soil organic carbon ($g \cdot kg^{-1}$)	Soil total N ($g \cdot kg^{-1}$)	Soil total P ($g \cdot kg^{-1}$)	Soil available K ($g \cdot kg^{-1}$)	Soil pH (H_2O)
20	2220	0.9	14.1	9.0	8.9	0.028	26.11	1.04	0.32	0.17	6.1
35	602	0.7	19.4	17.5	20.3	0.245	25.47	1.22	0.31	0.18	5.8
53	594	0.7	23.0	22.2	25.8	0.501	24.95	1.15	0.31	0.18	5.6
69	519	0.7	26.9	25.7	26.9	0.700	17.20	1.11	0.38	0.18	5.6

Biomass estimation

To quantify the biomass of different aboveground tree components (leaves, branches, stembark, stemwood), we collected ten analytic trees of *L. olgensis* with varying ages from 7 to 69 years old from the forest inventory data in the farm. On the basis of these data, we developed allometric regression models for each tree component and total aboveground biomass of *L. olgensis*. All the regression models were statistically highly significant (all $R^2 > 0.93$, $p<0.001$) (Table 2). Thus, in the present study, the biomasses of the different tree components were estimated from the developed models, instead of cutting down the whole tree.

Table 2. Regression models for biomass estimation of different tree components of *Larix olgensis*

Component	Regression equation	R^2
Leaves	$W=0.1546(D^2H)^{0.3410}$	0.957
Branches	$W=0.1838(D^2H)^{0.5212}$	0.931
Stembark	$W=0.0422(D^2H)^{0.6443}$	0.966
Stemwood	$W=0.0494(D^2H)^{0.8842}$	0.985
Total aboveground	$W=0.2386(D^2H)^{0.7363}$	0.972

Notes: *W* is biomass (dry weight, kg); *D* is diameter at breast height (cm); *H* is height of the tree (m).

Chemical analyses

All the plant samples were oven-dried to a constant weight at 65°C and ground in a mill for nutrient analyses. The samples were digested in H_2SO_4–$HClO_4$ at 380°C, and then the extracts were analyzed for N, P, K, Ca and Mg concentrations. N and P concentrations were determined colorimetrically on a continuous-flow autoanalyzer (AutoAnalyzer III, Bran+Luebbe GmbH, Germany). K concentration was determined by flame photometer method. Ca and Mg concentrations were determined by EDTA titrations (Dong et al. 1996).

Statistical analyses

Nutrient contents in the various aboveground tree components were estimated by multiplying respective nutrient concentration and biomass of each tree component (dry weight measurements). Rate of nutrient removal ($kg \cdot ha^{-1} \cdot a^{-1}$) was estimated by multiplying the nutrient content in the harvested parts of the tree and stand density and then dividing by the stand age.

One-way analysis of variance (ANOVA) was used to test the effects of stand age on nutrient concentrations in each tree component. The least significant difference (LSD) test was used to separate the means and differences were considered significant

(p<0.05). Statistical analyses were performed using SPSS (v. 11.5).

Results

Biomass of different aboveground tree components

The biomass of all aboveground tree components increased consistently with increasing stand age, but the increase in biomass varied greatly among different tree components. The total aboveground biomass of individual tree still increased by 32% with stand age from 53 to 69 years old. In all stands, the proportion of biomass in different tree components to total aboveground biomass was in the order of stemwood (62%–83%), branches (9%–21%), stembark (7%–11%) and leaves (1%–6%), (Table 3). Moreover, the proportion of each tree component biomass to total aboveground biomass was different among different stand ages. The proportion of stemwood biomass increased consistently from 62% to 83% and the proportions of other tree components decreased simultaneously with stand age from 20 to 53 years old. On the contrary, the proportions of all tree component biomass remained constant with stand age from 53 to 69 years old (Table 3).

Table 3. Aboveground biomass (kg·tree^{-1}) and allocation (%, in the parentheses) in various aboveground tree components of different-aged *Larix olgensis*

Aboveground tree components	Aboveground biomass (kg·tree^{-1})			
	Stand age (years)			
	20	35	53	69
Stemwood	16.62(62.3)	114.98(78.1)	210.27(81.5)	282.64(83.1)
Stembark	2.93(11.0)	11.72(8.0)	18.61(7.2)	23.09(6.8)
Branches	5.67(21.2)	17.43(11.8)	25.32(9.8)	30.15(8.8)
Leaves	1.46(5.5)	3.04(2.1)	3.88(1.5)	4.35(1.3)
Total tree	26.68	147.18	258.07	340.22

Nutrients in various aboveground tree components

In all stands, the concentration of N, P, K and Mg was highest in leaves and lowest in stemwood, and followed the order of leaves, branches, stembark and stemwood. By contrast, Ca concentration was highest in stembark (Fig. 1). Variations in nutrient concentrations among stand ages depended on both tree components and nutrient elements. With increasing stand age, the concentration of all elements (except Ca) in stemwood decreased significantly. The concentration of stembark Ca, branch N, P and K significantly increased, while leaf K concentration significantly decreased and leaf Ca concentration increased (Fig. 1).

The accumulation rates of all nutrients tended to decline with increasing stand age for all tree components, particularly in stemwood. However, the slope of the decline in nutrient accumulation rate varied greatly. For example, with increasing stand age from 53 to 69 years old, total aboveground N, P and Mg contents increased by <10%, while total aboveground K and Ca contents still increased by 25% and 33%, respectively (Table 4).

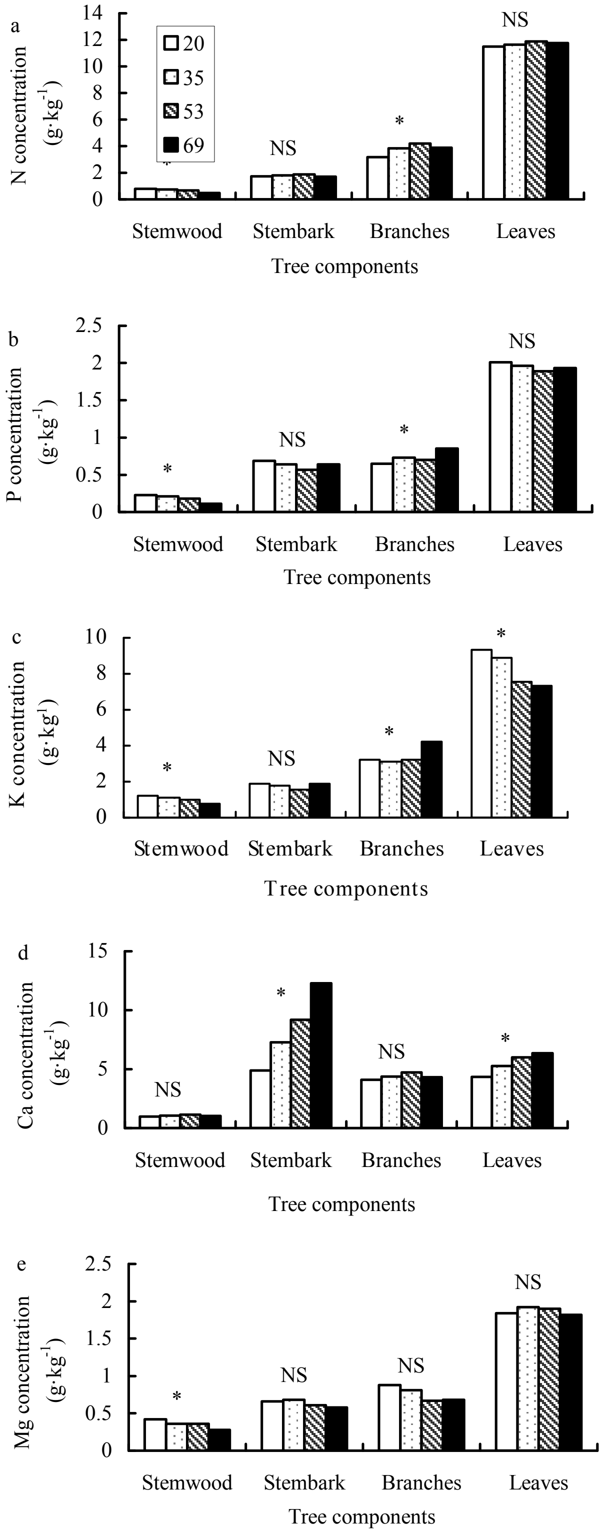

Fig. 1 Mean nutrient concentrations (g·kg^{-1}) from different nutrient elements in the aboveground tree components of different-aged *Larix olgensis*. * stands significant difference among ages at p<0.05 (Scheffe's test); NS stands insignificant difference among ages.

For all elements in various aboveground tree components, Ca content in the stembark was higher than that in the branches and leaves in three older stands, and N and K contents in leaves were

higher than those in stembark in many cases (Table 4). The proportions of nutrient stocks in different tree components to total aboveground nutrient stocks differed greatly from those of biomass. For example, the biomass of stemwood accounted for 62%–83% of total aboveground biomass, but the nutrient stock in stemwood only accounted for 25%–68% of total aboveground nutrient stock across all stands (25%–43% of N, 31%–52% of P, 35%–59% of K, 27%–43% of Ca, and 42%–68% of Mg, respectively), (Table 4). The nutrient allocation pattern in various tree components also varied with stand age, mainly in leaves and stemwood. The proportions of all nutrient stocks in leaves decreased consistently with increasing stand age, whereas the proportions in stemwood increased with age firstly from 20 to 53 years old and then decreased with age from 53 to 69 years old (Table 4). The proportions of nutrient stocks in branches and stembark were relatively constant with increasing stand age (Table 4).

Table 4. Nutrient content (g·tree^{-1}) and allocation (%, in the parentheses) in the aboveground tree components of different-aged *Larix olgensis*

Aboveground tree components	N				P				K			
	Stand age (years)				Stand age (years)				Stand age (years)			
	20	35	53	69	20	35	53	69	20	35	53	69
Stemwood	13.3	86.2	140.9	138.5	3.8	24.1	37.8	31.1	20.4	124.2	199.8	220.5
	(25.0)	(41.2)	(43.0)	(40.0)	(30.7)	(48.0)	(51.5)	(38.9)	(35.3)	(55.0)	(58.9)	(51.8)
Stembark	5.1	21.1	34.8	39.2	2.1	7.5	10.6	14.8	5.6	20.4	29.6	44.1
	(9.6)	(10.1)	(10.6)	(11.3)	(16.2)	(14.9)	(14.4)	(18.5)	(9.6)	(9.0)	(8.7)	(10.4)
Branches	18.0	66.6	106.1	117.3	3.7	12.7	17.7	25.6	18.3	53.9	80.5	128.7
	(33.9)	(31.8)	(32.4)	(33.9)	(29.6)	(25.3)	(24.1)	(32.1)	(31.6)	(23.9)	(23.8)	(30.3)
Leaves	16.8	35.4	46.1	51.1	2.9	6.0	7.3	8.4	13.6	27.1	29.2	32.0
	(31.5)	(16.9)	(14.0)	(14.8)	(23.5)	(11.8)	(10.0)	(10.5)	(23.5)	(12.0)	(8.6)	(7.5)
Total tree	53.1	209.3	327.8	346.2	12.5	50.3	73.5	79.9	57.9	225.6	339	425.3

Aboveground tree components	Ca				Mg			
	Stand age (years)				Stand age (years)			
	20	35	53	69	20	35	53	69
Stemwood	16.3	123.0	237.6	291.1	7.0	41.4	75.7	79.1
	(27.0)	(40.9)	(43.0)	(39.7)	(42.1)	(59.7)	(68.0)	(65.4)
Stembark	14.3	85.4	171.0	283.3	1.9	8.0	11.4	13.4
	(23.8)	(28.4)	(31.0)	(38.7)	(11.7)	(11.5)	(10.2)	(11.1)
Branches	23.3	76.3	120.0	130.5	5.0	14.1	17.0	20.5
	(38.7)	(25.4)	(21.7)	(17.8)	(30.1)	(20.4)	(15.2)	(17.0)
Leaves	6.3	16.0	23.3	27.6	2.7	5.8	7.4	7.9
	(10.5)	(5.3)	(4.2)	(3.76)	(16.2)	(8.4)	(6.6)	(6.5)
Total tree	60.3	300.8	551.9	732.5	16.6	69.3	111.4	120.9

Discussion

Aboveground biomass and nutrient allocation

In the present study, the biomass allocation pattern in various aboveground tree components was similar in 20, 35, 53 and 69 years old *L. olgensis* plantations (stemwood > branches > stembark > leaves). In contrast, Yang et al. (1995) studied the biomass allocation pattern in 5–25 years old *L. olgensis* plantations, and found that the relative contribution of different tree component biomass in 21–25 years old stands was the same as that in the present study, but varied obviously among ages before 20 years old. The aboveground biomass allocation pattern in various tree components also varied with larch species. For example, several studies found that the biomass was in the order of stemwood > stembark > branches > leaves for *L. gmelinii* plantations at ages of 20–80 (Liu et al. 1990; Liu et al. 1994; Sun et al. 2007), whereas the same order of total aboveground biomass allocation as the present study was observed in *L. principis-rupprechtii* and *L. leptolepis* plantations at comparable ages (Liu et al. 1995; Kim 1999).

With few exceptions, the nutrient allocation pattern in various tree components was similar to the biomass allocation pattern (i.e. stemwood > branches > stembark > leaves). Stemwood had the highest nutrient content for all elements in all stands due to its highest biomass, which is consistent with many studies for other tree species (e.g. Laclau et al. 2000; Ponette et al. 2001). As compared with 62%–83% contribution of stemwood biomass to total aboveground biomass, the 25%–68% contribution of nutrient stock in stemwood to total aboveground nutrient stock was relatively lower. This can be ascribed to the lowest nutrient concentrations in stemwood. As an exception, Ca stock in stembark was higher than that in branches and leaves. The highest Ca content in stembark was also widely observed (e.g. Laclau et al. 2000; Peri et al. 2006), which was ascribed to the structural function of Ca in the cell wall (Lambers et al. 1998).

For biomass allocation pattern, the proportions of different tree component biomass to total aboveground biomass varied obviously with stand age from 20 to 53 years old, while the proportions remained nearly constant from 53 to 69 years old (Table 3). This suggested that aboveground biomass allocation in various tree components tended to be stable as the stand matures, which is consistent with studies on other tree species (Laclau et al. 2000). The contribution of stemwood to total aboveground nutrient stock for all elements increased consistently with stand

ages from 20 to 53 years old, mainly owing to the increased contribution of stemwood biomass (Tables 3, 5). However, the proportion of nutrient stock in stemwood to total nutrient stock decreased considerably with stand ages from 53 to 69 years old (Table 5).

Table 5. Estimated rate of nutrient removal (kg·ha^{-1}·a^{-1}) by harvesting of *Larix olgensis* plantations with different harvest schemes at different ages

Harvesting schemes	Harvest age (years)	N	P	K	Ca	Mg
Total above-ground biomass	20	5.84	1.37	6.37	6.63	1.82
	35	3.60	0.87	3.88	5.17	1.19
	53	3.67	0.82	3.80	6.19	1.24
	69	2.60	0.60	3.20	5.51	0.91
Stemwood + stembark	20	2.02	0.64	2.86	3.37	0.98
	35	1.85	0.54	2.49	3.58	0.85
	53	1.97	0.54	2.57	4.58	0.98
	69	1.34	0.34	1.99	4.32	0.70
Stemwood debarked	20	1.46	0.42	2.25	1.79	0.77
	35	1.48	0.41	2.14	2.12	0.71
	53	1.59	0.42	2.24	2.66	0.85
	69	1.04	0.23	1.66	2.19	0.60

Nutrient removal by different harvest schemes

In timber forestry, the appropriate criteria for determining the optimal forest rotation length have been debated for a long time. The tree growth process and economic benefit are the two main determinants (Newman 2002). The tree age, at which mean annual increment of stem volume maximized, was traditionally deemed to be the optimal rotation age for trees under specific conditions (Newman 1988; Smith et al. 1996). In recent decades, in addition to tree growth and economic benefit, nutrient budgets have attracted increasing attention in forest management, because soil nutrient depletion in short and medium rotation plantations has been observed worldwide (Laclau et al. 2000; Ponette et al. 2001).

In Northeast China, pure plantations of *L. olgensis* were officially designated to be clear-cut at more than 40 years old, according to the maximum mean annual increment of stem volume. However, some researchers suggested that the rotation age of *L. olgensis* plantation in Northeast China could be shortened to 20–35 years old for maximizing economic benefit (Liu & Yu 1990; Zhao & Jiang 1995). The timber of *L. olgensis* is more suitable to be used as pole rather than as sawlog, considering its structural characteristics (Bergstedt and Lyck 2003). Thus, with increasing demand for small and medium diameter timber, the economic benefit of producing small and medium diameter timber is substantially higher than that of producing large diameter timber. To evaluate the effects of rotation length and logging scheme on nutrient removal by timber harvesting, we estimated the rate of nutrient removal (kg·ha^{-1}·a^{-1}) with three logging schemes at different ages of *L. olgensis* plantations (Table 5). Nutrient removal was highly dependant on the harvest age of stands, because nutrient stock and its allocation differed greatly at different stages of stand development (Tables 4, 5). Moreover, the effects of harvest age on the rate of nutrient removal by harvesting varied greatly with logging scheme (Table 5). Specifically, for the harvest of total aboveground biomass, the rates of nutrient removal of all elements were highest when trees were harvested at 20 years old, lowest at 69 years old, and were moderate and similar at 35 and 53 years old. For the harvest of stemwood or stem with bark (stemwood + stembark), rates of nutrient removal of all elements were similar when trees were harvested at 20, 35 and 53 years old, and were considerably lower when trees were harvested at 69 years old, except that the rate of Ca removal was highest when trees were harvested at 53 years old (Table 5). These results indicated that shortening rotation length for *L. olgensis* plantation from 53 to 20 years would not change the rates of nutrient removal of all elements by harvesting stemwood or stem with bark. However, for the harvest total aboveground biomass, shortening rotation length would greatly increase the rate of nutrient removal.

Though shortening rotation length for *L. olgensis* plantation cannot influence the rate of nutrient removal by the harvest of stem only, the intensive harvesting practice of shorter rotation can accelerate the soil nutrient depletion, owing to increased soil nutrient loss by compaction and destruction of surface soil and slow nutrient turnover of harvest residues (Pennock & van Kessel 1997; Finér et al. 2003). For example, Murphy et al. (2004) reported 8% decrease in stem volume and 60% decrease in economic potential as influenced by the compaction of topsoil in 21-year-old *Pinus radiata* plantation. Therefore, the indirect effects of harvesting practice on ecosystem nutrient cycling (i.e. soil nutrient erosion, litter decomposition) instead of direct nutrient removal by the harvest of stem are probably the primary factors, leading to the accelerated soil nutrient depletion in shorter rotation of *L. olgensis* plantations. As substantial amount of nutrients was accumulated in the crown and stembark, nutrient removal by harvesting strongly depended on the logging scheme. Harvesting of stem with bark (stemwood + stembark) is the most commonly practiced technique in the harvest of larch trees in China. This logging scheme resulted in the removal of 35%–54% of N, 47%–58% of P, 45%–62% of K, 51%–79% of Ca and 54%–78% of Mg accumulated in aboveground tree biomass. Debarking would allow a considerable reduction in nutrient loss for all elements (Table 5). The effect of debarking on nutrient removal would be greatest for Ca, as stembark contained 24%–39% of Ca, while contained less than 20% of all other elements (Table 4).

Conclusions

For *L. olgensis* plantations in Northeast China, aboveground biomass and nutrient allocation patterns varied considerably through stand development. The proportion of stemwood biomass to total aboveground biomass increased consistently whereas that of other tree component biomass to total aboveground biomass decreased with stand age from 20 to 53 years old, and then kept relatively constant with stand age from 53 to 69 years old. The variations in aboveground nutrient allocation through stand development were mainly in leaves and stemwood.

The proportion of nutrient stock in stemwood to total aboveground nutrient stock firstly increased with stand age from 20 to 53 years old and then decreased with stand age from 53 to 69 years old, while the proportion of leaves decreased consistently with stand age. Shortening length of time for rotation of *L. olgensis* plantation from 53 to 20 years would not change the rate of nutrient removal by the harvest of stem, but would greatly increase the rate of nutrient removal by the harvest of total aboveground biomass. Thus, the harvest of all aboveground biomass should be avoided for *L. olgensis* plantations in northeast China, particularly for short rotation plantations. Besides, debarking on site is recommended to conserve soil fertility (particularly Ca) and maintain the high productivity over successions. In order to completely evaluate the impacts of timber harvest on ecosystem nutrient cycling and to optimize the harvest age of stand and logging schemes, it is needed to study the nutrient cycling processes affected by harvesting practices, due to the important role of indirect effects of harvesting practice on soil nutrient depletion.

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